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EFFECTS OF ROUGHNESS AND SUCTION ON TRANSITION FROM LAMINAR TO TURBULENT FLOW

Hugh L. Dryden

Director, National Advisory Committee for Aeronautics

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Introduction

The very large gains in performance of aircraft which would be obtained if the flow in the boundary layer were everywhere laminar have constantly attracted the interest of the research worker to the phenomenon of transition. Considerable progress has been made in understanding the many factors which influence transition and some practical use has been made of methods of stabilizing the laminar layer to delay transition, as for example, in the so-called laminar-flow airfoils designed to give a falling pressure over a large part of the upper surface. Laminar-flow airfoils have been somewhat disappointing in practice because they are so sensitive to roughness and waviness. Even small particles of dust or water adhering to the surface may produce early transition to turbulent flow.

In recent years attention has turned to another method of stabilizing the laminar boundary layer, that of removing some of the boundary layer air through a porous boundary by

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applying suction. At the Third Anglo-American Conference held at Brighton, England, in 1951, Sir Melvill Jones and M. R. Head presented a paper entitled "The Reduction of Drag By Distributed Suction", which described flight experiments on this matter. Some of the results indicated a large unfavorable effect of small roughness, although apparently a considerable degree of stabilization by suction was obtained. Other experiments have also indicated the same stabilizing effect of suction, but the results seem to me to be disappointing in the light of the results to be inferred from the Tollmien-Schlichting theory of the stability of a laminar boundary layer. The adverse element again seems to be unavoidable surface roughness.

It will be a long time before all aspects of the transition problem are understood, not only because a complete theory must include non-linear effects, but also because experiments must be performed over extremely wide ranges of the many variables, not attainable in any single apparatus. Many of the variables, such as wind-tunnel turbulence and surface roughness, are difficult to measure. I believe, however, that the main features of transition are suggested by the data at hand. This brief note, containing some speculation as well as facts, is an attempted assessment of the effect of roughness in reducing the gains attainable through the use of suction.

Tollmien-Schlichting Theory of Boundary-Layer Stability

It is now well established that in the absence of large disturbances the breakdown of laminar flow begins by the selective amplification of any small disturbances present as described by the theory developed by the Göttingen group during the period 1924-35 and here called the Tollmien-Schlichting theory. Experimental confirmation was obtained by Schubauer and Skramstad in 1940 (reference 1).

The Tollmien-Schlichting theory yields the result that for any given distribution of mean velocity, small disturbances will be amplified or damped by an amount dependent on their frequency or wave-length, the displacement thickness of the boundary layer and the Reynolds number based on the displacement thickness. Below a certain "critical" Reynolds number all disturbances are damped; at higher Reynolds numbers certain selected disturbances will be amplified, i.e., those within certain regions of wave length or frequency. The selected disturbances travel with characteristic velocities less than the free stream velocity.

Initial disturbances arise from such sources as the initial turbulence of the free airstream, acoustic waves, the flow deflection at the front stagnation point, and surface roughness. These disturbances may be described by a spectrum, and the most significant part of the spectrum is that corresponding to the most highly amplified waves. These are usually of wave lengths much longer than the boundary layer thickness. It is believed that transition occurs when the amplitude of the waves has increased to the point where local separation occurs intermittently. It is known that transition does not occur when the initial disturbance is sufficiently small until considerable amplification occurs.

As shown in the experiments of Schubauer and Skramstad, if the mean velocity distribution is changing along the surface, the selectively amplified disturbances increase and decrease in amplitude according to the stability characteristics of the local distribution. If the disturbances are small, we may speculate that their effects might be additive. Experiment shows that "small" must be interpreted to mean an amplitude less than 1/4 percent of the mean speed of the boundary layer.

Theoretical Results for Boundary-Layer Suction

We shall consider the case of a flat plate in a flow of uniform free stream velocity, U, with suction uniformly applied through a homogeneous porous surface. The flow coefficient, c_Q, defined as the ratio of the volume flow through a unit area of the surface to the free stream velocity, is then constant. At the leading edge the velocity distribution in the boundary layer approaches the Blasius distribution characteristic of the plate without suction but at a considerable distance from the leading edge the distribution approaches asymptotically an exponential distribution. At any value of x the distribution is a function of $c_Q\sqrt{Ux/\nu}$ where x is the distance from the leading edge and ν is the kinematic viscosity of the fluid. The displacement thickness δ^* approaches the limiting value ν/c_QU at large values of x. Figure 1 shows $c_QU\delta^*/\nu$ as a function of $c_Q\sqrt{Ux/\nu}$ as computed by Iglisch (reference 2).

The critical Reynolds number $Re^*_c = (U\delta^*/\nu)_c$ above which some disturbances are amplified has been computed for the smooth plate without pressure gradient or suction by several investigators. We shall use Schlichting's approximate value of 575 for comparison with the results of computations by similar methods, although Lin's later result, 420, is probably more accurate. For the asymptotic suction profile (exponential distribution) Pretsch obtained 55,200 as compared with 70,000 obtained by Bussmann and Münz. These values compare with Pretsch's 10,000 to 20,000 for a plate without suction but with large favorable pressure gradient. The maximum amplification parameter in the unstable region was reduced by suction from 3.45×10^{-3} to 4.65×10^{-4}. The critical Reynolds numbers for the intermediate profiles between the leading edge and the asymptotic distribution were computed by Ulrich (reference 3) and are shown in figure 2 as a function of $c_Q\sqrt{Ux/\nu}$.

By combination of the data of figures 1 and 2 the value of c_Q required to stabilize the boundary layer at each value of x may be computed. Thus, one plots on figure 2 the variation of $Re^* = U\delta^*/\nu$ for several values of c_Q as computed from figure 1. The result is shown in figure 3. All points above the stability limit correspond to amplified disturbances which lead to transition. Thus, for small values of c_Q, laminar flow occurs only very near the leading edge. For values of c_Q greater than 1.18×10^{-4}, laminar flow is maintained at all values of x. At intermediate values of c_Q, disturbances are first damped, then amplified, and later damped with increasing x. The tangency of the Re* and Re^*_c curves for $c_Q = 1.18 \times 10^{-4}$ occurs at a value of $c_Q \sqrt{Ux/\nu}$ of 0.16. The value of Re^*_c at this point is about 3.7 times that for the plate without suction.

Since suction produces a thinning of the laminar boundary layer, the value of x at which a certain value of Re* is to be found varies with the suction flow coefficient. For example, figure 4 shows the variation of Ux/ν at which Re* is equal to 600 with c_Q. Many investigators have confused this rearward motion of transition with increasing suction due to the thinning of the boundary layer with the stabilizing effect of suction predicted by the Tollmien-Schlichting theory. Stabilization can be demonstrated only if Re* at transition is increased. This observation is not intended to deny that the effects of suction in thinning the boundary layer may have important practical applications. But such gains are very small compared to those possible if the theoretical stabilization effect can be realized in practice.

Effects of Roughness on Transition

I have reviewed elsewhere the available experimental results on the effect of roughness on transition (reference 4). We shall limit ourselves here to single two-dimensional roughness elements consisting of cylindrical wires or rods placed on a flat plate in uniform flow. When such an element is introduced on the plate, the transition position may be moved upstream from its original location but still remain at a considerable distance downstream from the roughness element. Thus, one cannot conclude that the maintenance of a laminar mean velocity distribution for a considerable distance behind the roughness element indicates no effect of the element in producing earlier transition.

The roughness effect proved to be dependent on the ratio of the height k of the roughness element to the displacement thickness δ^*_k of the boundary layer at the element, provided the conditions were such that transition was at least a few inches downstream from the element. The effect of roughness is not reduced by increased turbulence of the free stream. In fact, a plot of the ratio of the transition Reynolds number of the rough plate to that for the smooth plate against the relative height of the roughness k/δ^*_k gives a good correlation of the available data when transition occurs appreciably downstream from the roughness element. At a certain value of k/δ^*_k dependent on the stream speed, location of roughness element, and airstream turbulence, the transition position reaches the element and remains there as the height or the stream speed is further increased.

Figure 5 gives the data obtained on flat plates without pressure gradient or suction in terms of $Re^*_t = (U\delta^*/\nu)_t$ rather than the Reynolds number $Re_t = (Ux/\nu)_t$ of reference 4. For the flat plate without pressure gradient or suction $Re_t = 0.337\ (Re^*_t)^2$. Since reference 4 was published, G. B. Schubauer's group at the National Bureau of Standards has kindly supplied the additional data at larger values of k/δ^*_k shown in figure 5. The difficulties of extending the curve are very great. Even in the NBS low turbulence tunnel for which the value of Re^*_o for the smooth plate is 2900 and assuming Re^*_o independent of the free stream speed, it was not possible to obtain results for k/δ^*_k greater than 1.3 while maintaining a transition position equal to or greater than three inches from the roughness element. The resulting value of Re^*_t/Re^*_o was 0.20. The lowest value of Re^*_t was about 580 which is of the same order as that obtained in a stream of 3 percent turbulence.

We have only limited information on roughness effects when pressure gradients are present as on an airfoil, and sufficient details are not available even in these cases for complete analysis. The critical Reynolds number varies with chordwise position on the airfoil because of the varying shape of the distribution of mean speed in the boundary layer. We would like to compare the transition Reynolds number for the rough airfoil with that for the smooth airfoil when transition occurs at the same chordwise position in each case. Such data are not available. But experience with laminar-flow airfoils indicates that roughness effects are still great even in the presence of large favorable gradients. Over the years as techniques for making smooth fair surfaces were improved, values of Re^*_t increased until a value of 7100 was finally obtained, but this value is only 2.4 times the zero pressure-gradient value as compared with ratios of the theoretical critical values of Re^*_c of 17 to 35. I believe that much of this discrepancy is due to roughness effects, although we cannot expect the transition values to exactly follow the critical values.

Roughness on the nose of an airfoil appears to be less critical. The disturbance introduced is damped downstream until the region of minimum pressure is reached. Hence, a given k/δ^*_k at the nose is equivalent to a smaller value at the point of minimum pressure. Except for this effect we may speculate that the presence of a cylindrical roughness element at $x = x_k$ reduces the critical Reynolds number of all downstream sections in some such ratio as indicated by figure 5. For roughness elements of other shapes, a similar curve could be determined.

Experimental Data on Effect of Suction on Transition

The only results on the effect of suction for the case of zero pressure gradient are those of Sir Melvill Jones and M. R. Head previously mentioned. The model was an airfoil designed to give a long run with uniform pressure. Transition occurred at a value of Re^*_t less than 1890 without suction and the maximum value of Re* which could be investigated was 2980. Perhaps the relatively low value without suction was due to roughness.

With suction applied sufficient to give laminar flow up to the maximum attainable Reynolds number, a single roughness element 0.006 inch in height placed 12 inches from the leading edge completely eliminated the stabilizing effect of suction. At this location under the test conditions $c_Q\sqrt{Ux/\nu}$ was 2.72 so that the mean velocity distribution was not far from the asymptotic distribution and the theoretical value of Re^*_c was at least 100 times greater than for the plate without suction. The value of k/δ^*_k for the roughness element was 1.4. This surprising observation leads me to guess that roughness elements of the order of $1\frac{1}{2}$ times the displacement thickness in height give rise to a disturbance level so great that the transition Reynolds number falls to values of the order of 585 regardless of the stability of the boundary layer ahead of the element. If this is true, the permissible roughness height may be of the order of one-half the displacement thickness or less, if the stabilizing effect of suction is to be realized in practice.

Combined Effects of Roughness and Suction

The value of k/δ^*_k for the asymptotic distribution is simply $c_Q\ Uk/\nu$, independent of x since δ^*_k is constant with x. The ratio of k/δ^*_k at any value of $c_Q\sqrt{Ux_k/\nu}$ to the asymptotic value of k/δ^*_k is shown in figure 6. If some value of k/δ^*_k,

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less than 0.5 we find that k must be less
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to be at x_k = 0.0 3 feet. Here k/δ^*_k
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than 0.00047 inch o limit k/δ^*_k to 0.5.
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value with suction should still be about
plate without suction.
xperimental data available it is not
the value of k/δ^*_k which might be per-
in a higher critical Reynolds number than
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orrelation of figure 5 for boundary layers
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lotted curve, rounding off to a value of
ing to Re^*_t of the order of 580. Thus, for
on case the asymptotic value of Re^*_t/Re^*_o
be about 0.008.

Concluding Remarks

I have not attempted to discuss the more complicated effects to be expected on airfoils for which the effects of pressure gradients must also be considered. It seems to me that there is no well authenticated case of any large stabilizing effect of suction in the sense of greatly increased transition Reynolds number based on displacement thickness of the boundary layer. Most of the observed effects can be accounted for by the thinning of the boundary layer on the assumption of nearly constant Re^*_t. It is obvious that only an extensive program carefully planned in the light of our present knowledge of roughness effects can settle the question as to whether the theoretically predicted stabilization of the flow can be obtained in practice.

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2. Iglisch, R.: Exakte Berechnung der laminaren Grenzschicht an der längsangeströmten ebenen Platte mit homogener Absaugung. Schriften der Deutschen Akademie der Luftfahrtforschung, Band 8 B, Heft 1, 1944. Translated in NACA Technical Memorandum No. 1205.

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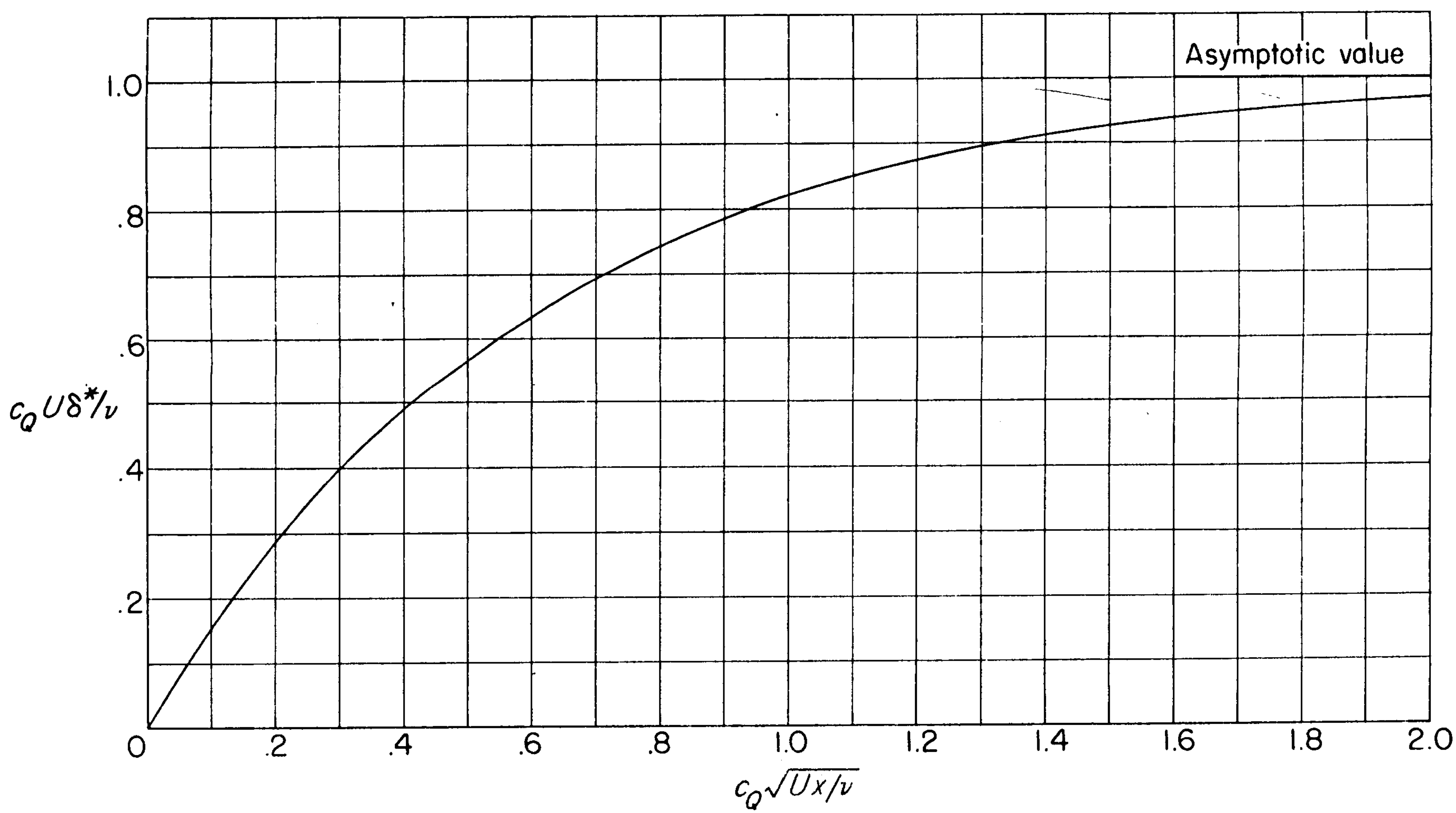


Figure 1.- Displacement thickness parameter $c_Q U\delta^*/\nu$ as function of $c_Q\sqrt{Ux/\nu}$ for flat plate with uniform suction.

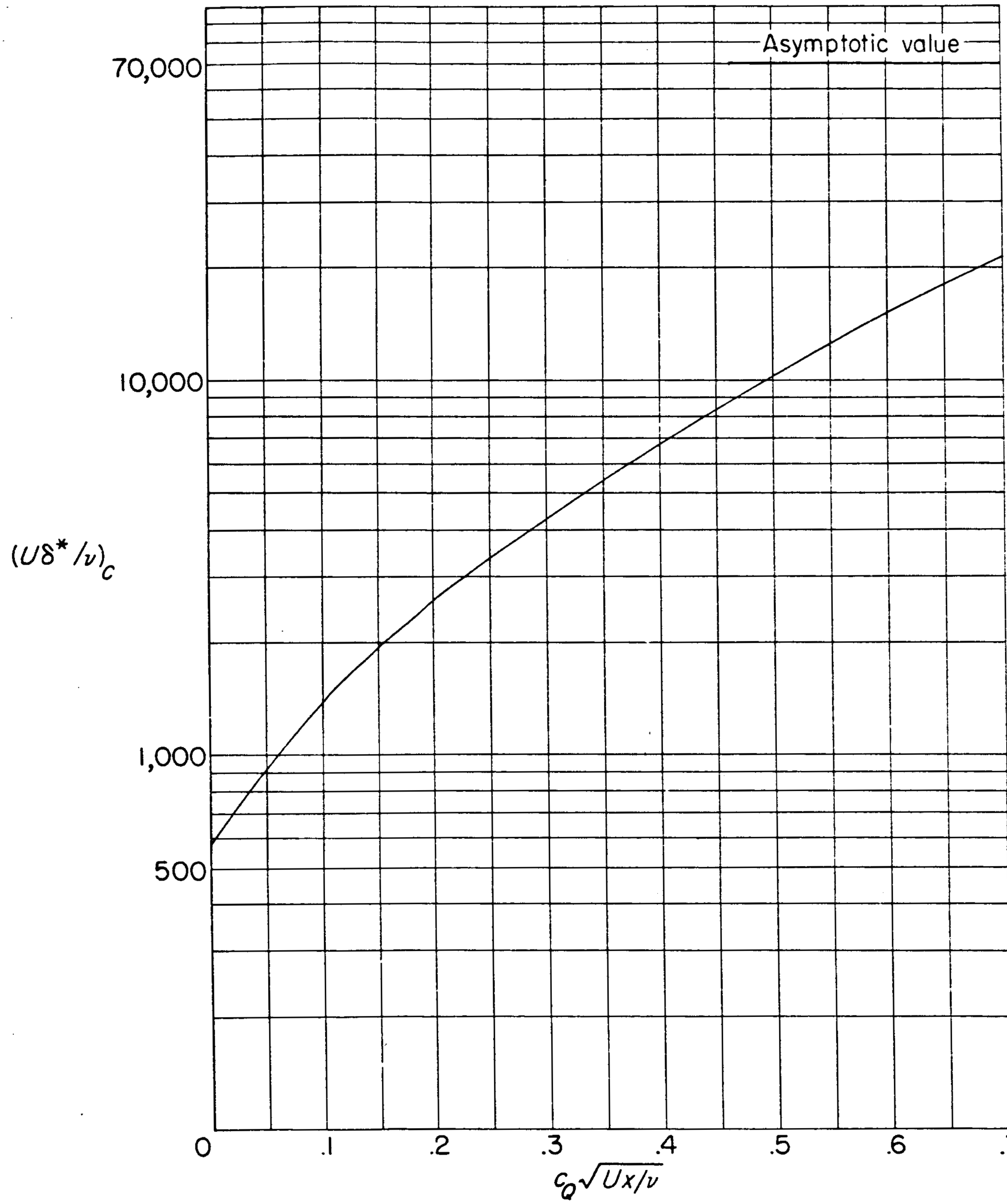


Figure 2.- Critical Reynolds number $(U\delta^*/\nu)_c$ as a function of $c_Q\sqrt{Ux/\nu}$ for flat plate with uniform suction.

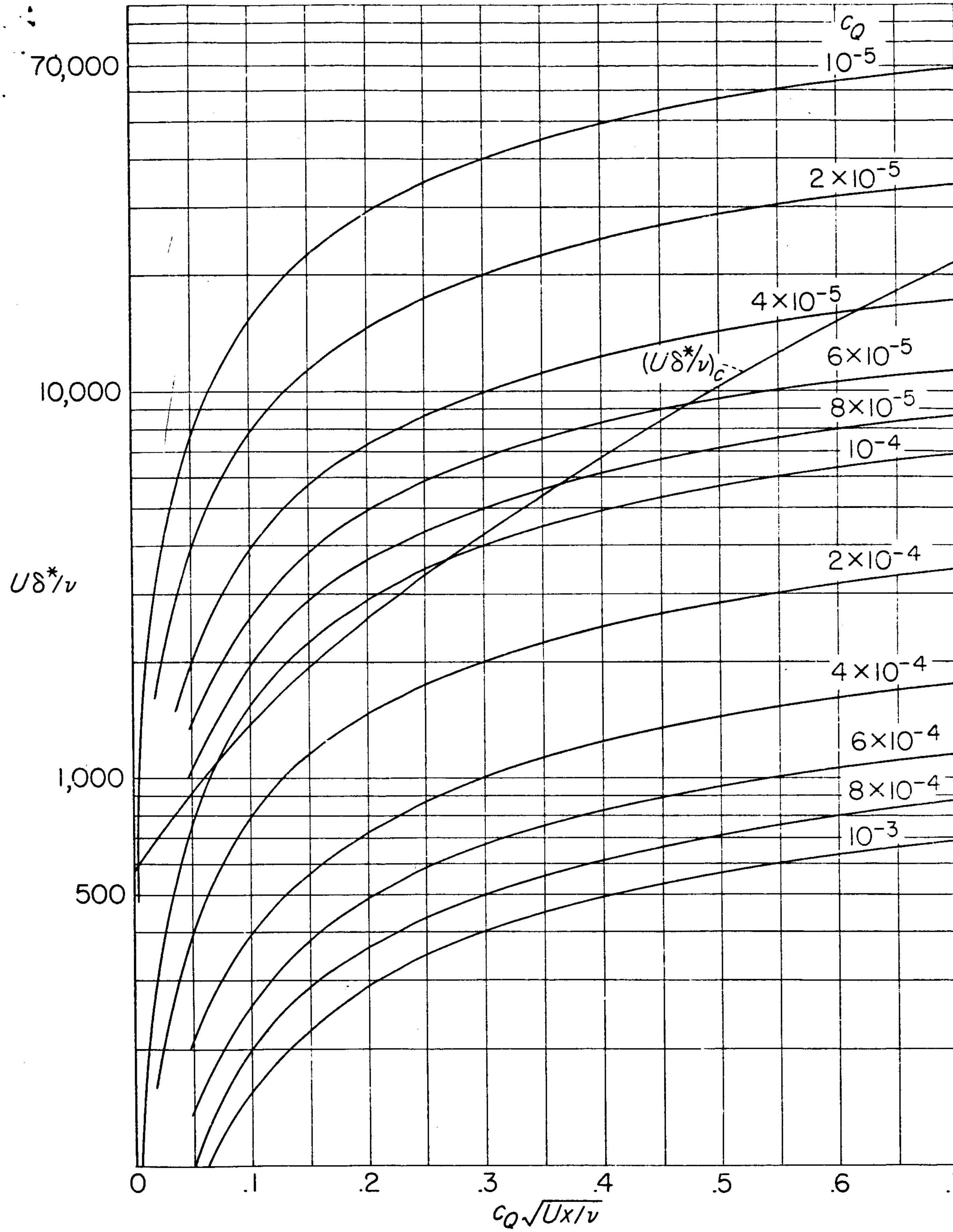


Figure 3.- Reynolds number $U\delta^*/\nu$ for various suction flow coefficients c_Q compared with critical Reynolds number for flat plate with uniform suction.

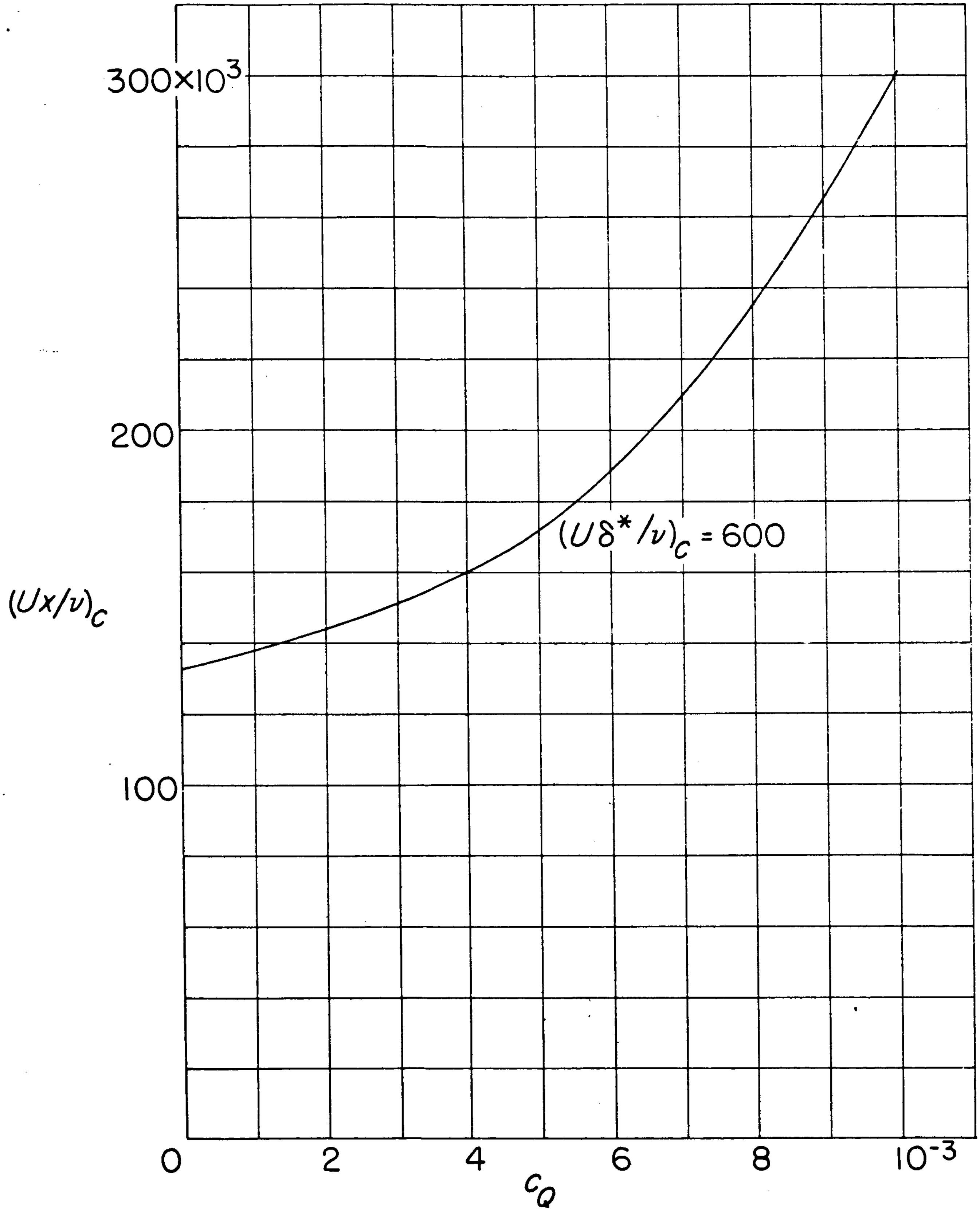
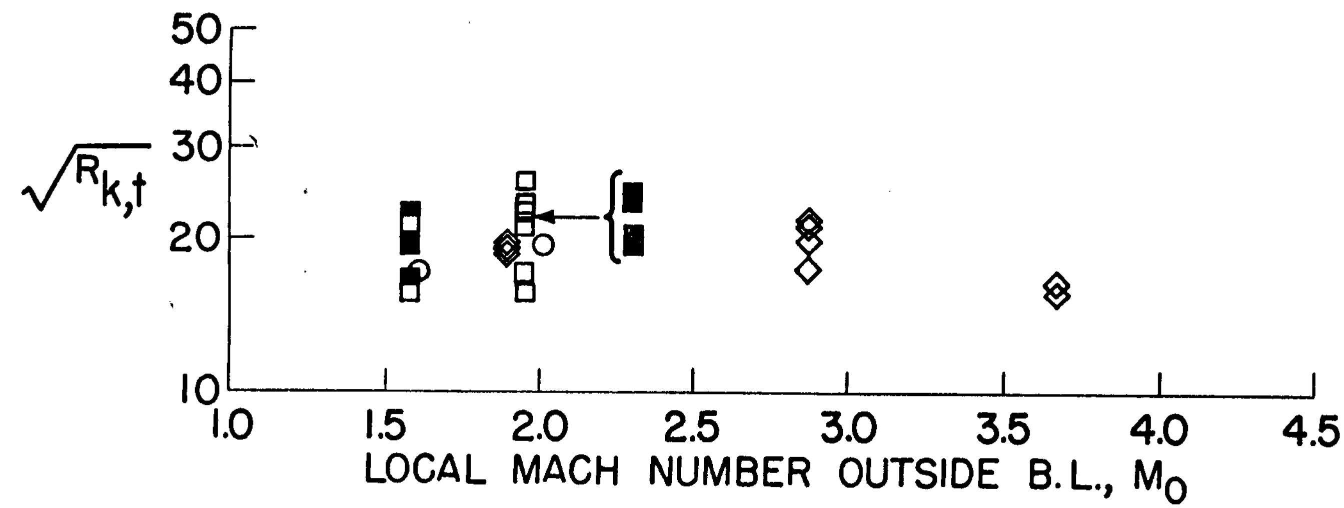


Figure 4.- Reynolds number $(Ux/\nu)_c$ corresponding to constant critical Reynolds number $(U\delta^*/\nu)_c$ of 600 as function of suction flow coefficient c_Q.



	REFERENCE	CONFIGURATION	ROUGH.	T_w/T_O
○13	BRASLOW, KNOX, & HORTON	FLAT PLATE	SPHERICAL	ADIAB.
□	"	CONE	GRANULAR	"
■	"	"	"	M_O=1.58, 1.289; M_O=1.95, 1.423
◇14	VAN DRIEST & MC CAULEY	"	SPHERICAL	ADIAB.

Figure 5.- Effect of supersonic Mach number on the roughness Reynolds number for transition.

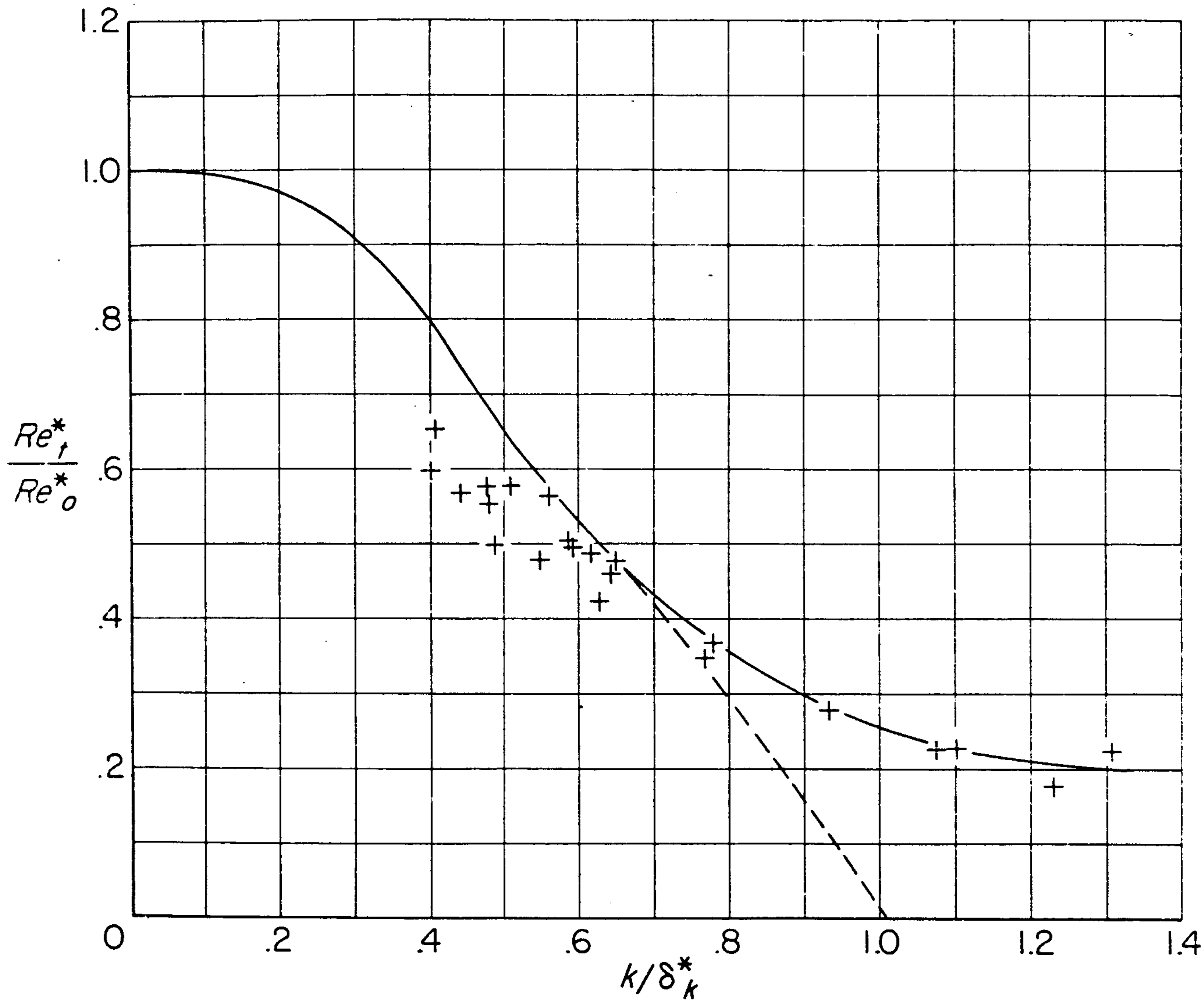


Figure 5.- Ratio of transition Reynolds number $(U\delta^*/\nu)_t = Re^*_t$ of rough plate to that of smooth plate Re^*_o as a function of the ratio of the height of roughness element to displacement thickness at element for single two-dimensional cylindrical and flat strip elements.

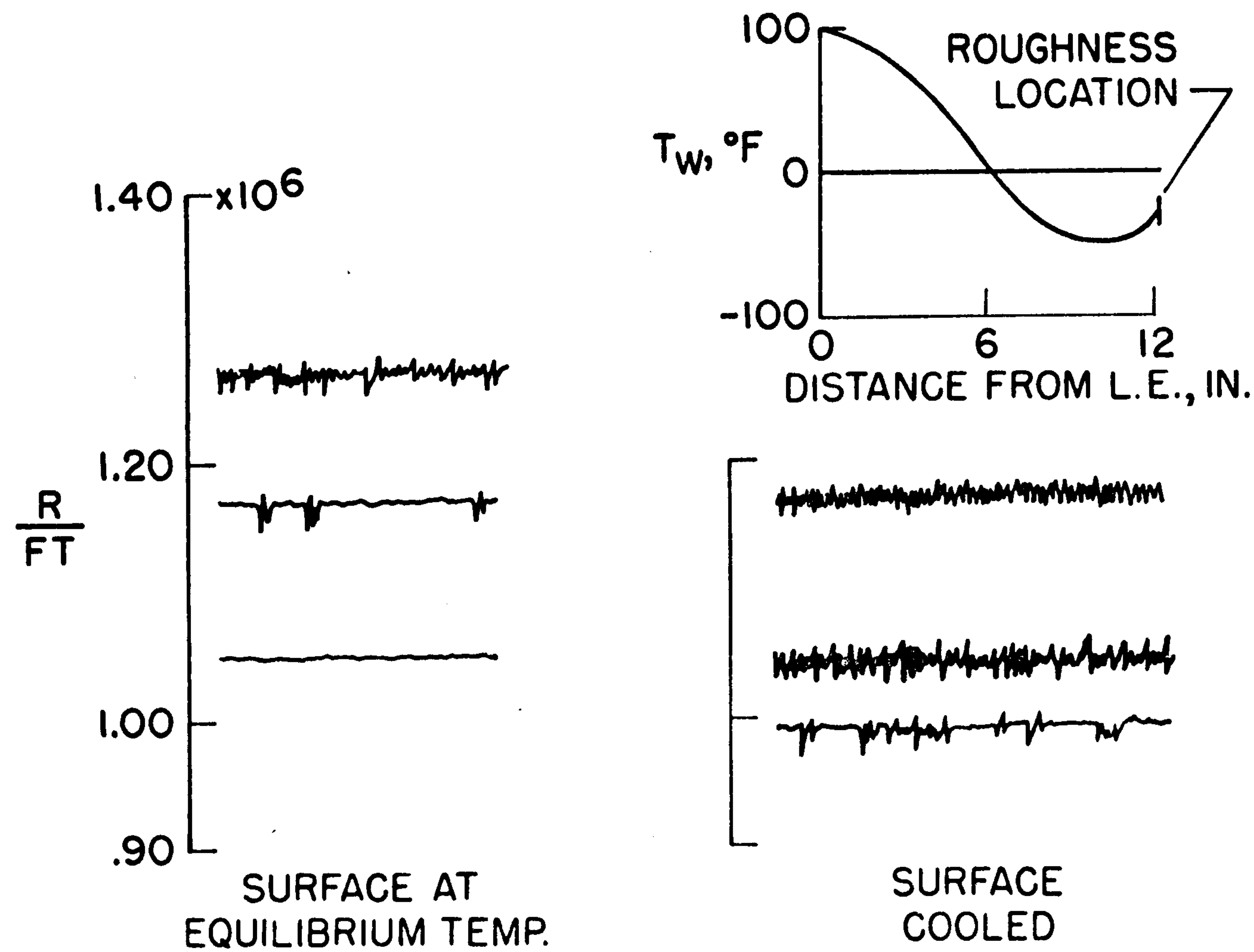


Figure 6.- Comparison of oscillograph records for 10° cone surface near adiabatic-wall temperature and cooled; 0.017-inch roughness at 12.5 inches from apex; $M_{\infty} = 2.01$.

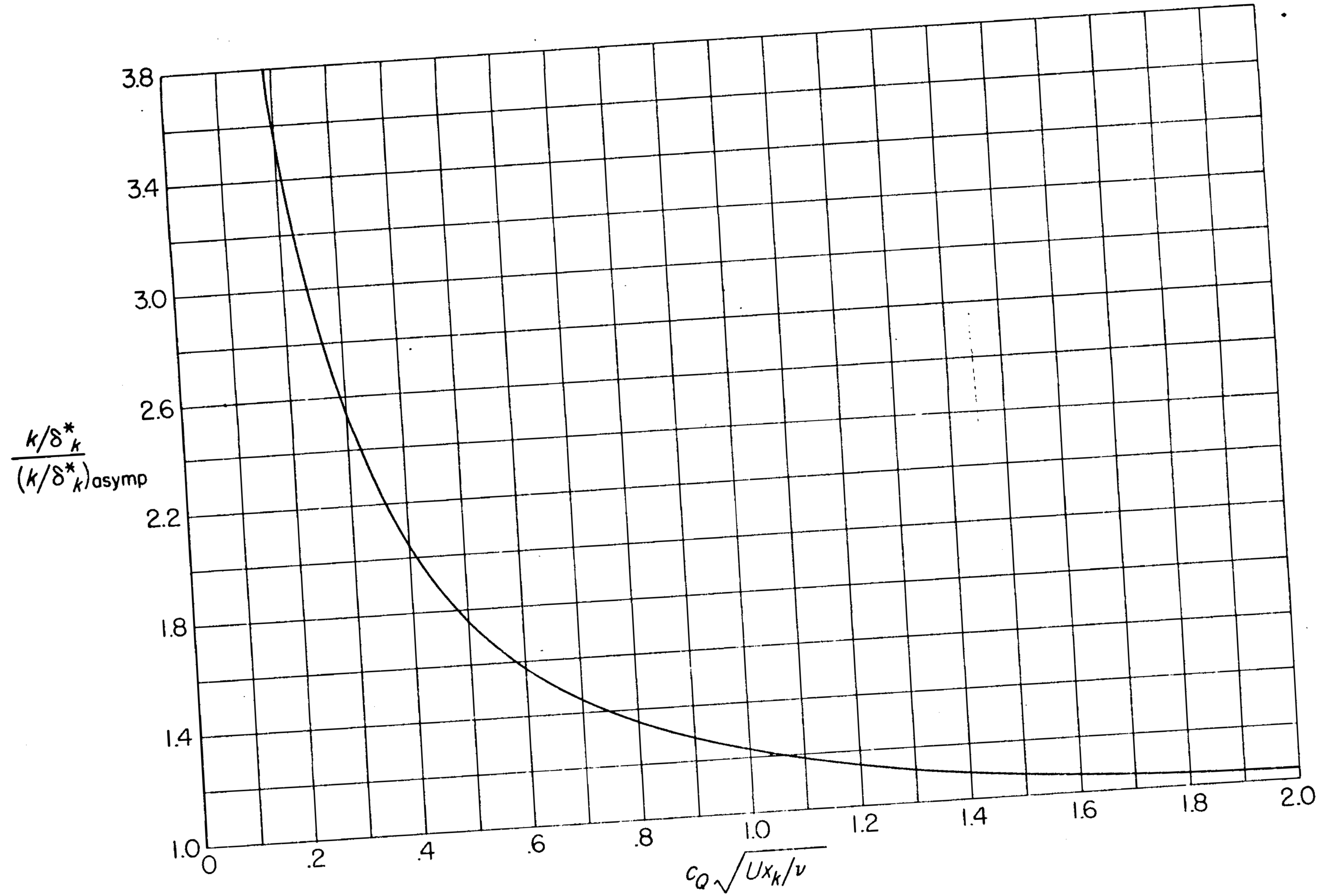


Figure 6.- Effect of $c_Q\sqrt{Ux_k/\nu}$ on the value of k/δ_k^*.

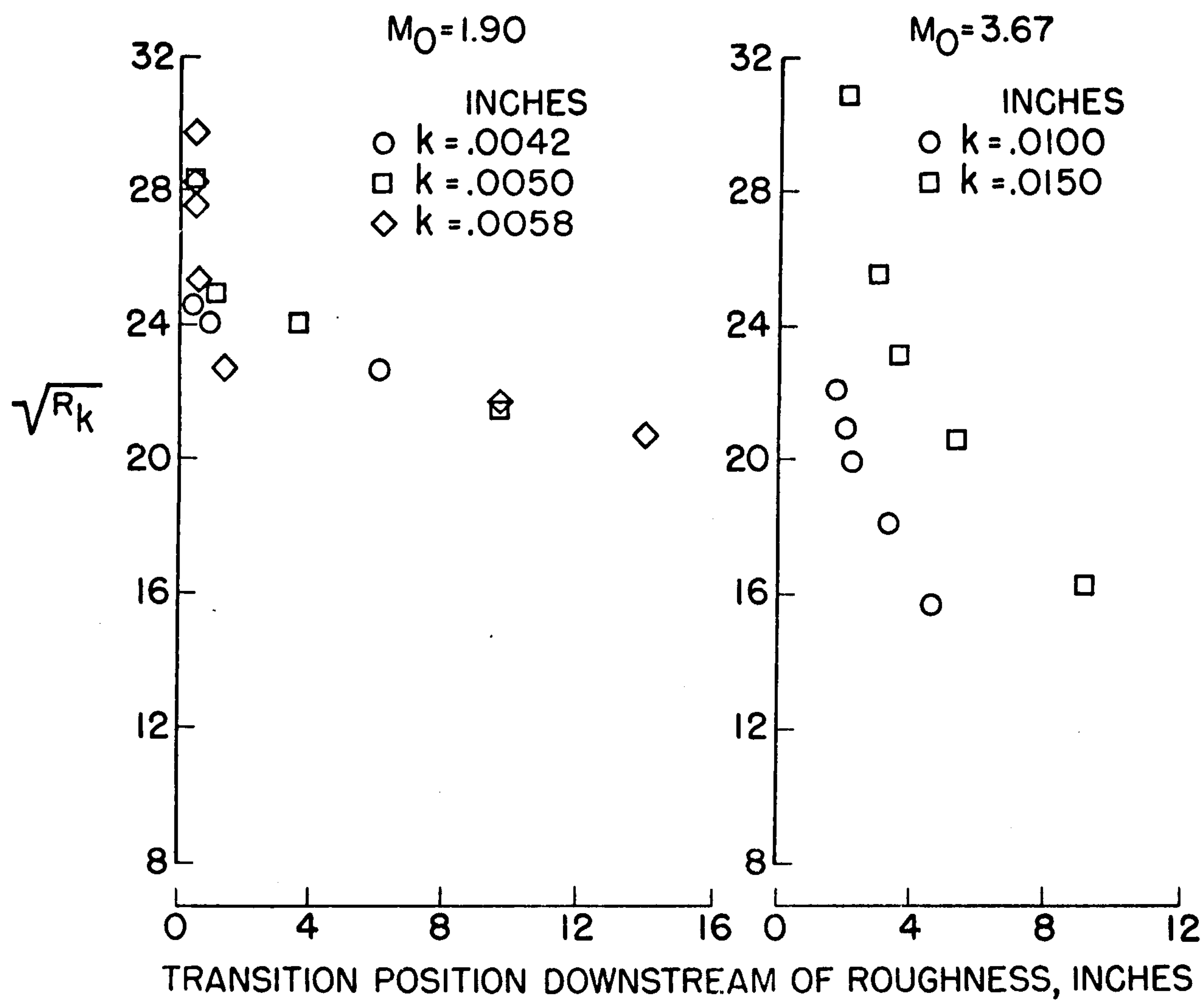


Figure 7.- Forward movement of fully developed turbulent boundary layer with increasing three-dimensional roughness Reynolds number.